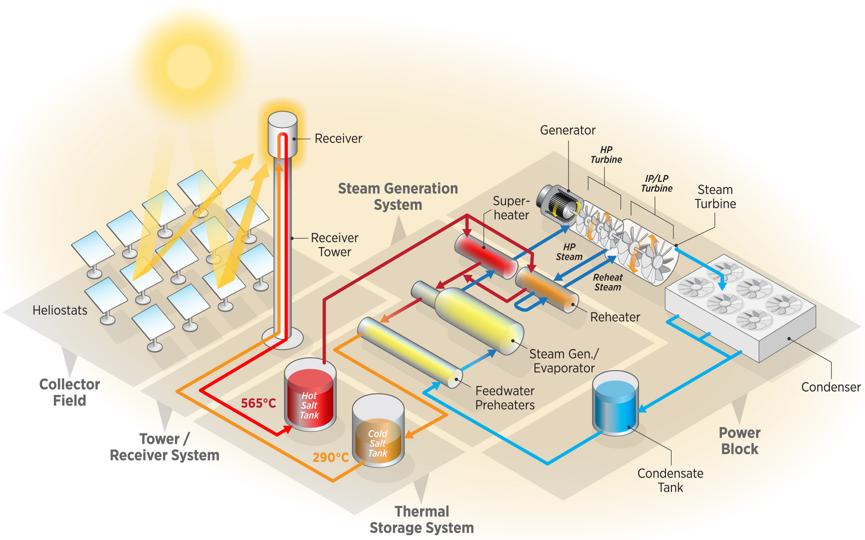
Optimizing the Design of Concentrated Solar Power Plants

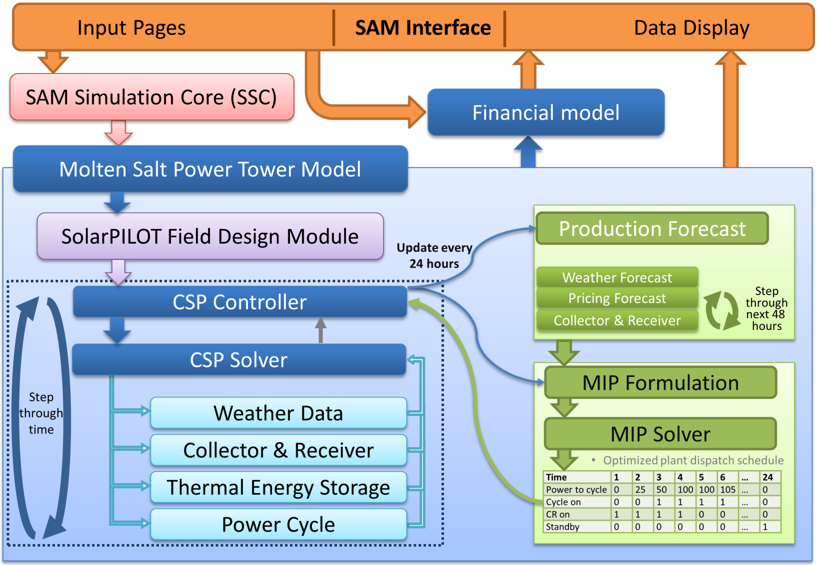
Jeffrey Larson   Sven Leyffer   Michael Wagner

DOE Office of Energy Efficiency & Renewable Energy

March 2, 2017


Receiver
Receiver Tower
Heliostats
Collector Field
Tower / Receiver System
Steam Generation System
Super-heater
Generator
HP Turbine
IP/LP Turbine
Steam Turbine
HP Steam
Reheat Steam
Reheater
Steam Gen./ Evaporator
Feedwater Preheaters
Condenser
Power Block
Condensate Tank
565°C
Hot Salt Tank
290°C
Cold Salt Tank
Thermal Storage System

Modeling CSP with thermal energy storage



Time	1	2	3	4	5	6	...	24
Power to cycle	0	25	50	100	100	105	...	0
Cycle on	0	0	1	1	1	1	...	0
CR on	1	1	1	1	0	0	...	0
Standby	0	0	0	0	0	0	...	1

Inner, dispatch MIP optimization

- Example variables:

$y_t^{csb} =$ 1 if cycle is in standby mode at time t; 0 otherwise
$y_t^{rsup} =$ 1 if receiver is starting up at time t and was not in standby mode at time $t-1$; 0 otherwise

Inner, dispatch MIP optimization

- Example variables:

$$
\begin{aligned}
y_t^{csb} &= 1 \text{ if cycle is in standby mode at time } t\text{; 0 otherwise} \\
y_t^{rsup} &= 1 \text{ if receiver is starting up at time } t \text{ and was not in standby} \\
&\quad \text{mode at time } t-1\text{; 0 otherwise}
\end{aligned}
$$

- Example constraints:
  - Standby and start-up modes can't coincide
  - Total power produced by the receiver must account for both the available energy and any start-up energy consumption

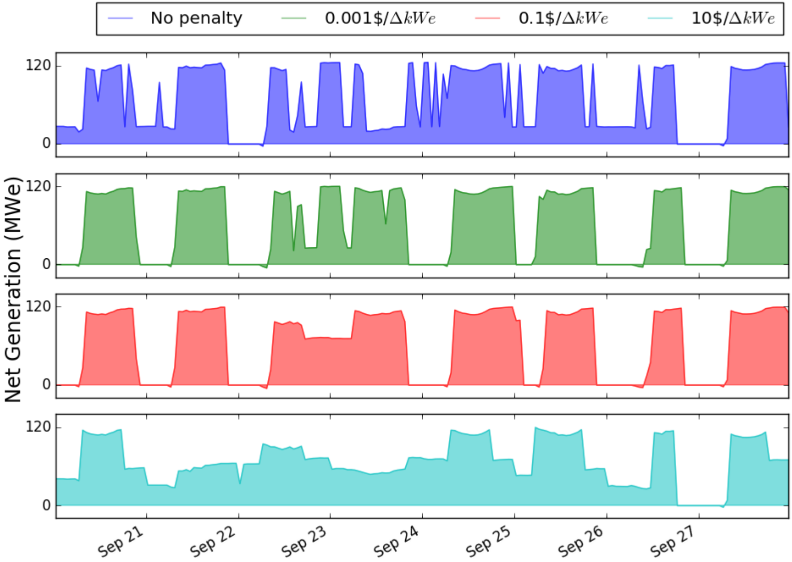
Inner, dispatch MIP optimization

- Example variables:

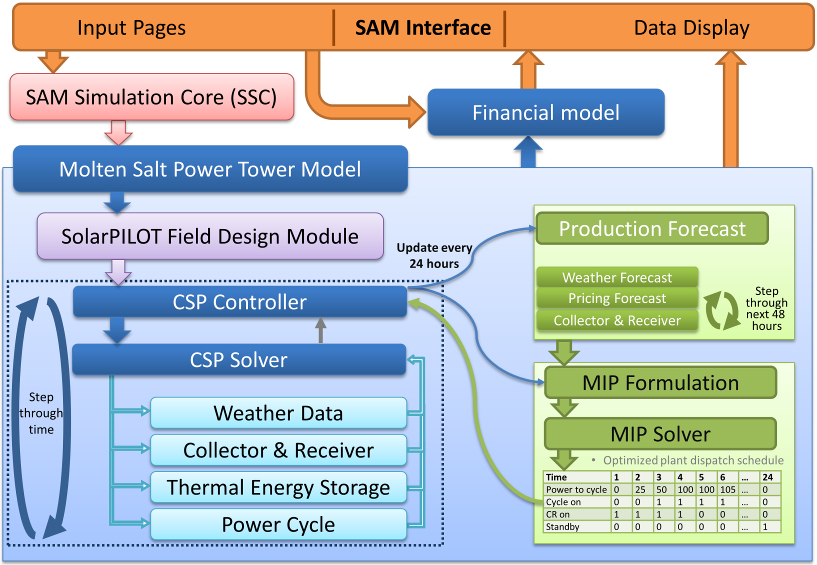
$y_t^{csb} = 1$ if cycle is in standby mode at time t; 0 otherwise
$y_t^{rsup} =$ 1 if receiver is starting up at time t and was not in standby mode at time $t-1$; 0 otherwise

- Example constraints:
  - Standby and start-up modes can't coincide
  - Total power produced by the receiver must account for both the available energy and any start-up energy consumption
- Objective:
  - (electricity price)(power generated) - (parasitic losses) - (penalties)
  - Penalties: cycle start-up, receiver start-up, and change in electricity production between time steps

Inner, dispatch MIP optimization



Modeling CSP with thermal energy storage



Time	1	2	3	4	5	6	...	24
Power to cycle	0	25	50	100	100	105	...	0
Cycle on	0	0	1	1	1	1	...	0
CR on	1	1	1	1	0	0	...	0
Standby	0	0	0	0	0	0	...	1

Outer optimization

Design variables:

- Tower height
- Receiver diameter
- Receiver height
- Receiver DNI design point
- Solar multiple
- Cycle design point conversion efficiency
- Cycle design point power output
- TES capacity
- Mirror degradation replacement threshold
- Number of panels per heliostat (even integer)
- Number of full-time staff available for heliostat repairs (integer)
- Number of full-time staff available for mirror washing (integer)

Outer optimization

- Evaluate the performance of a given CSP plant (with TES) using NREL's System Advisor Model (SAM)

Outer optimization

- Evaluate the performance of a given CSP plant (with TES) using NREL's System Advisor Model (SAM)

- Initial objective: optimize the revenue produced by SAM

Outer optimization

- Evaluate the performance of a given CSP plant (with TES) using NREL's System Advisor Model (SAM)

- Initial objective: optimize the revenue produced by SAM

- We don't want to treat this as just a "black-box"

Outer optimization

- Evaluate the performance of a given CSP plant (with TES) using NREL's System Advisor Model (SAM)
- Initial objective: optimize the revenue produced by SAM
- We don't want to treat this as just a "black-box"
- Much can be gained by exposing the problem structure to the optimization algorithm

Exposing structure

For example, say one wants to solve:

$$\text{minimize } f(x) = (f_1(x) - T_1)^2 + (f_2(x) - T_2)^2,$$

where f_1, f_2 are outputs from an expensive numerical simulation.

Exposing structure

For example, say one wants to solve:

$$\text{minimize}\, f(x) = (f_1(x) - T_1)^2 + (f_2(x) - T_2)^2\,,$$

where $f_1,\ f_2$ are outputs from an expensive numerical simulation.

- Assume $f_i : \mathbb{R} \to \mathbb{R}$ and $\begin{bmatrix} T_1(x) \\ T_2(x) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$

Exposing structure

For example, say one wants to solve:

$$\text{minimize}\, f(x) = (f_1(x) - T_1)^2 + (f_2(x) - T_2)^2 ,$$

where f_1, f_2 are outputs from an expensive numerical simulation.

- Assume $f_i : \mathbb{R} \to \mathbb{R}$ and $\begin{bmatrix} T_1(x) \\ T_2(x) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$
- If $\begin{bmatrix} f_1(a) \\ f_2(a) \end{bmatrix} = \begin{bmatrix} -1 \\ 1 \end{bmatrix}$ and $\begin{bmatrix} f_1(b) \\ f_2(b) \end{bmatrix} = \begin{bmatrix} 1 \\ -1 \end{bmatrix}$,

Exposing structure

For example, say one wants to solve:

$$\text{minimize } f(x) = (f_1(x) - T_1)^2 + (f_2(x) - T_2)^2 \, ,$$

where f_1, f_2 are outputs from an expensive numerical simulation.

- Assume $f_i : \mathbb{R} \to \mathbb{R}$ and $\begin{bmatrix} T_1(x) \\ T_2(x) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$
- If $\begin{bmatrix} f_1(a) \\ f_2(a) \end{bmatrix} = \begin{bmatrix} -1 \\ 1 \end{bmatrix}$ and $\begin{bmatrix} f_1(b) \\ f_2(b) \end{bmatrix} = \begin{bmatrix} 1 \\ -1 \end{bmatrix}$,
- then $f(a) = 2$ and $f(b) = 2$.

Exposing structure

For example, say one wants to solve:

$$\text{minimize}\, f(x) = (f_1(x) - T_1)^2 + (f_2(x) - T_2)^2\,,$$

where f_1, f_2 are outputs from an expensive numerical simulation.

- Assume $f_i : \mathbb{R} \to \mathbb{R}$ and $\begin{bmatrix} T_1(x) \\ T_2(x) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$
- If $\begin{bmatrix} f_1(a) \\ f_2(a) \end{bmatrix} = \begin{bmatrix} -1 \\ 1 \end{bmatrix}$ and $\begin{bmatrix} f_1(b) \\ f_2(b) \end{bmatrix} = \begin{bmatrix} 1 \\ -1 \end{bmatrix}$,
- then $f(a) = 2$ and $f(b) = 2$.

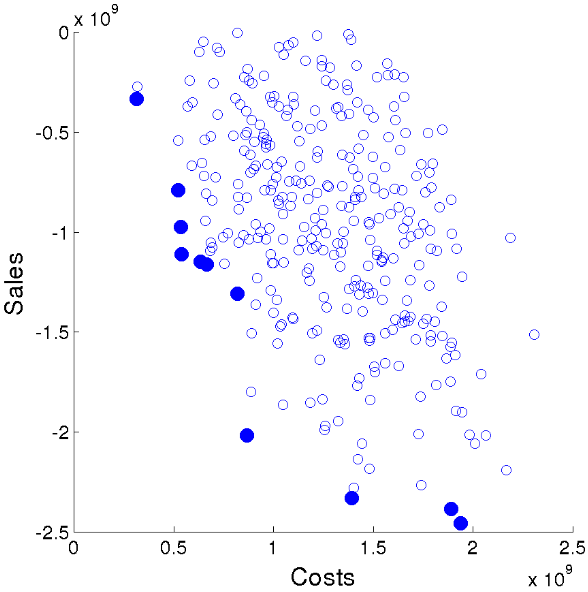
Let the optimization method model f_i and combine the model information to construct descent directions. This should do no worse (and very often better) than just modeling f.

Initial objective

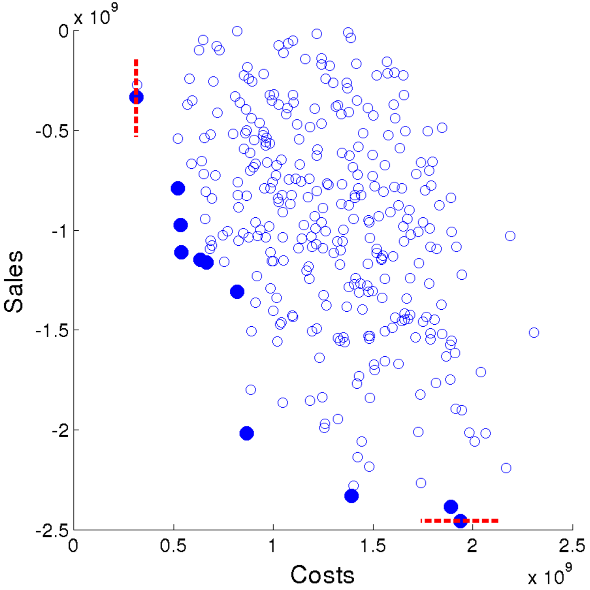
- Maximize Revenue: Minimize

$$-Sales + Costs$$

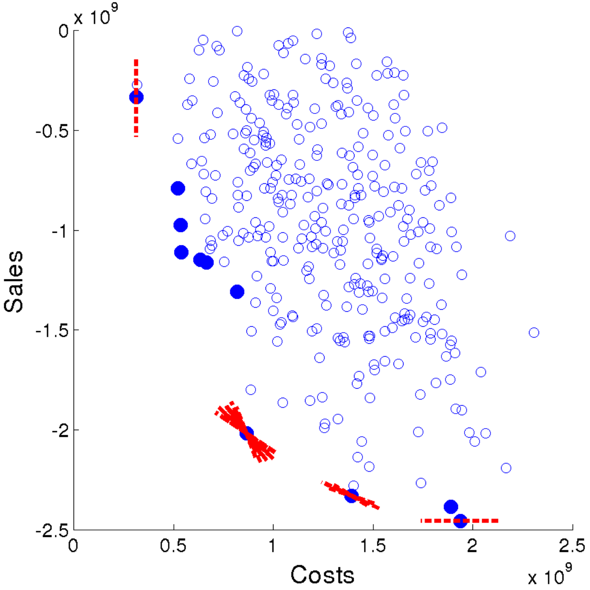
Initial objective



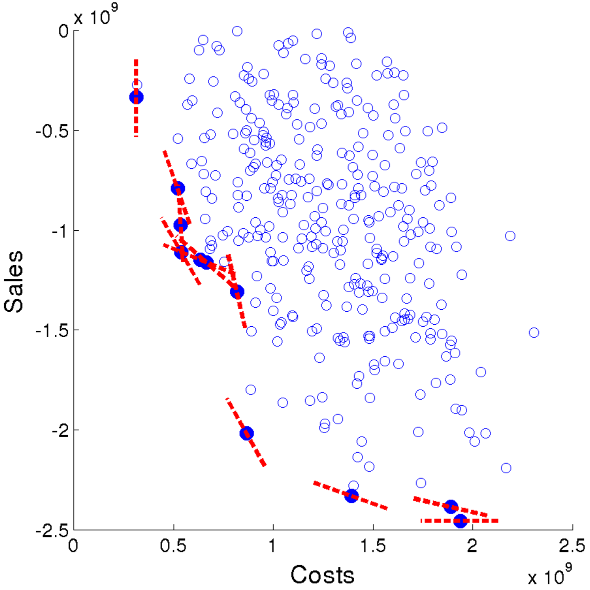
Initial objective



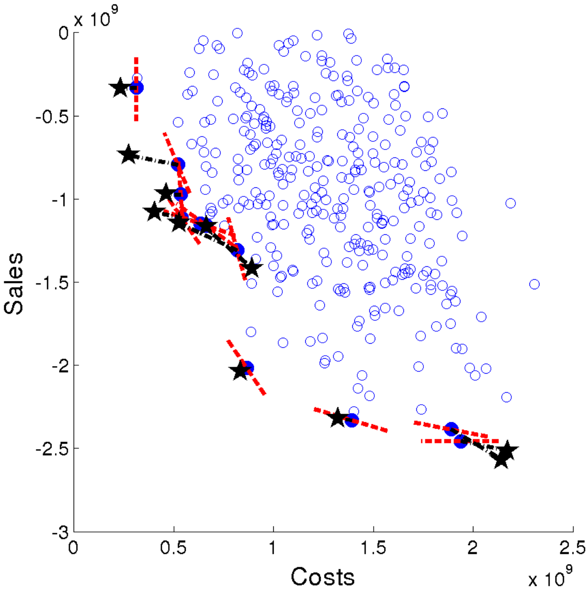
Initial objective



Initial objective



Initial objective



More exact objective description

$$R = f_e(x)$$

f_e: Explicit (known) costs

- Tower cost, receiver cost, O&M costs

More exact objective description

$$R = f_e(x) + f_d(s_d(x))$$

f_e: Explicit (known) costs

- Tower cost, receiver cost, O&M costs

s_d: Design simulation

- Call SolarPILOT to create a heliostat field

More exact objective description

$$R = f_e(x) + f_d(s_d(x)) + f_h(s_h(x, s_d, \xi_h))$$

f_e: Explicit (known) costs

- Tower cost, receiver cost, O&M costs

s_d: Design simulation

- Call SolarPILOT to create a heliostat field

s_h: Heliostat failure simulation

- Simulate heliostat failure due to mechanical, electrical events

More exact objective description

$$R = f_e(x) + f_d(s_d(x)) + f_h(s_h(x, s_d, \xi_h)) + f_o(s_o(x, s_d, \xi_o))$$

f_e: Explicit (known) costs

- Tower cost, receiver cost, O&M costs

s_d: Design simulation

- Call SolarPILOT to create a heliostat field

s_h: Heliostat failure simulation

- Simulate heliostat failure due to mechanical, electrical events

s_o: Optical degradation simulation

- Simulate mirror soiling and optical degradation

More exact objective description

$$R = f_e(x) + f_d(s_d(x)) + f_h(s_h(x, s_d, \xi_h)) + f_o(s_o(x, s_d, \xi_o)) + f_p(s_p(x, s_h, s_o))$$

f_e: Explicit (known) costs

- Tower cost, receiver cost, O&M costs

s_d: Design simulation

- Call SolarPILOT to create a heliostat field

s_h: Heliostat failure simulation

- Simulate heliostat failure due to mechanical, electrical events

s_o: Optical degradation simulation

- Simulate mirror soiling and optical degradation

s_p: Plant production

- Average over a set of fixed scenarios

More exact objective description

- Revenue isn't the best objective
  - \$1M plant making \$10M vs. \$1B plant making \$5B

More exact objective description

- Revenue isn't the best objective
  - \$1M plant making \$10M vs. \$1B plant making \$5B

- True objective f_T is some iterative calculation of the outputs of f_e, f_d, f_h, f_o, and f_p.

More exact objective description

- Revenue isn't the best objective
  - \$1M plant making \$10M vs. \$1B plant making \$5B

- True objective f_T is some iterative calculation of the outputs of f_e, f_d, f_h, f_o, and f_p.

- $f_T(f_e, f_d, f_h, f_o, f_p)$

More exact objective description

- Revenue isn't the best objective
  - \$1M plant making \$10M vs. \$1B plant making \$5B

- True objective f_T is some iterative calculation of the outputs of f_e, f_d, f_h, f_o, and f_p.

- $f_T(f_e, f_d, f_h, f_o, f_p)$

- Can get adjoint/derivative code for f_T (and all other f) via algorithmic differentiation.

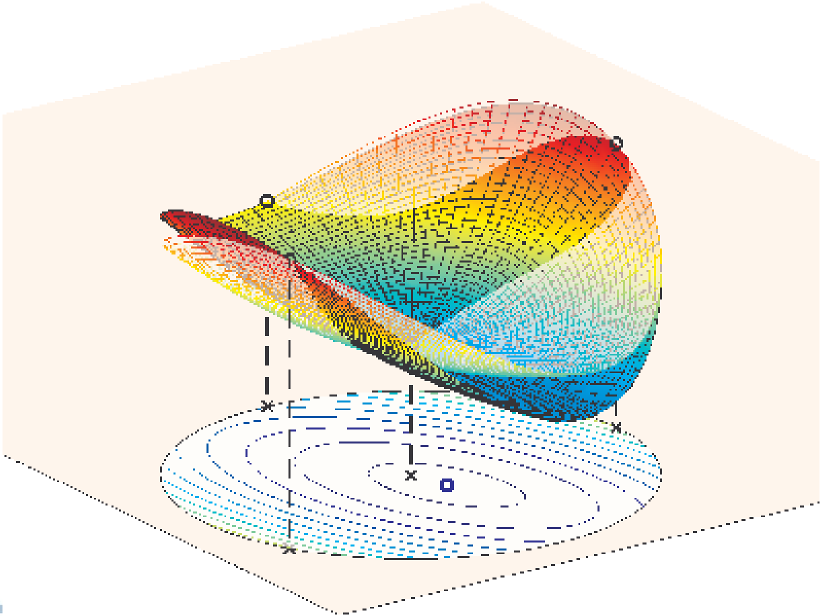
More exact objective description

- Revenue isn't the best objective
  - \$1M plant making \$10M vs. \$1B plant making \$5B
- True objective f_T is some iterative calculation of the outputs of f_e, f_d, f_h, f_o, and f_p.
- $f_T(f_e, f_d, f_h, f_o, f_p)$
- Can get adjoint/derivative code for f_T (and all other f) via algorithmic differentiation.
- Then gradient at a point x just involves a chain rule calculation.

More exact objective description

- Revenue isn't the best objective
  - \$1M plant making \$10M vs. \$1B plant making \$5B
- True objective f_T is some iterative calculation of the outputs of f_e, f_d, f_h, f_o, and f_p.
- $f_T(f_e, f_d, f_h, f_o, f_p)$
- Can get adjoint/derivative code for f_T (and all other f) via algorithmic differentiation.
- Then gradient at a point x just involves a chain rule calculation.
- Model s_d via a model m_d and replace ∇s_d with ∇m_d.

Example model



Final comments

- Exposing structure should allow for improved optimization results.

Final comments

- Exposing structure should allow for improved optimization results.
- Best way to handle integer variables?

Final comments

- Exposing structure should allow for improved optimization results.
- Best way to handle integer variables?
- Optimizing revenue with a model-based method has already improved previous-best parameters.